

Presented at the 11th National Passive Solar Conference, Boulder, CO, June 8-14, 1986,
and published in the proceedings.

FIELD MEASUREMENTS OF LIGHT SHELF PERFORMANCE
IN A MAJOR OFFICE INSTALLATION

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July 1986

This work was supported by the Energy Services Department of the Pacific Gas and Electric Company and by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Equipment Division, and Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ABSTRACT

Electric lighting is a major component of electrical energy use in large commercial buildings and has additional significant impact on the cooling energy requirements. This paper evaluates the monitored performance of such an integrated lighting scheme in a recently completed 600,000-ft² office structure located in the San Francisco Bay Area. Decentralized data acquisition systems monitored 62 different locations in the building between May 1985 and January 1986, recording average illuminance levels and corresponding ambient lighting power usage across the north and south building sections. A graphic summary of data compares the performance of effectiveness of the building's lightshelf system for north and south orientations. One counterintuitive conclusion of the study is that the "dimmer" north side light shelf scheme exhibits a higher potential (69% reduction from full power) for electric light reduction than the "brighter" south side scheme (56% reduction).

1. INTRODUCTION

Electric lighting consumes 30% to 50% of the electrical energy used in large commercial buildings and has additional significant impact on the cooling energy requirements. The use of daylight for ambient illumination can substantially reduce this energy usage. However, along with these important benefits come potential penalties for daylighting designs whose actual performance is considerably different than the original design goals. A daylighting design that lags far behind the original targeted illumination levels may not achieve the projected electric light energy savings and associated peak load reductions. A design that consistently provides too much daylight, on the other hand, can be a liability due to increased solar heat gain and discomfort to occupants from glare and thermal gradients. The challenge of good daylighting design is to produce a solution that delivers the needed illuminance levels to the work spaces while avoiding the extremes of performance that generate these liabilities.

Over the last decade, an increasing emphasis on daylighting has fostered the development and use of new tools to predict the performance of daylighting schemes. The impressive progress of these new computer programs, nomographs and modeling techniques is marred only by the lack of documented examples of the performance of existing daylighted buildings that could validate their

predictions. The expense, inconvenience and expertise necessary to instrument and analyze an existing building have retarded the generation of a body of documented case studies from which to learn.

In 1985, Lawrence Berkeley Laboratory (LBL), with support from Pacific Gas and Electric Company, performed an extensive analysis of a recently completed daylighted office building in the San Francisco Bay Area. This innovative structure represents a major investment in daylighting by a large U.S. corporation seeking reduced energy consumption, lower peak electrical demand and improved employee productivity. The initial design was strongly driven by daylighting considerations with decisions based on thorough analysis using the best energy and illuminance design tools available at the time. The DOE 2 energy simulation program was applied to evaluate energy consumption patterns in the original building proposal. To this technique was added analysis based on scale models, first with a small mass/shading model, then with larger-scale daylighting models tested in LBL's Sky Simulation Facility. The resulting structure was one in which daylighting-related concerns played a major role.

The product of this design process is a five-story, 600,000-ft² office building occupied by 3000 technical personnel in open-plan offices. As shown in Figure 1, the rectilinear mass of the building is elongated along an east/west axis producing major fenestration surfaces facing roughly north and south. (The building actually faces approximately 25 degrees west of south.) Building functions lacking a strong relationship to daylighting are grouped into two explicit core units, designed with opaque surfaces and placed on the east and west ends of the building to prevent the adverse radiation aspects associated with these orientations. A central atrium provides light, visual interest, circulation and drama to the building's interior spaces.

An important strategy in the building's design is an explicit separation of systems providing task and ambient illumination. Ambient illumination is provided by daylighting backed-up by indirect fluorescent lighting when needed. Task lighting is provided by individually controlled fixtures built into each workstation. The building design pushed the limits of experimental daylighting techniques to provide ambient daylighting across the full 90-ft width from exterior wall to atrium edge. To accomplish this the exterior walls are fully

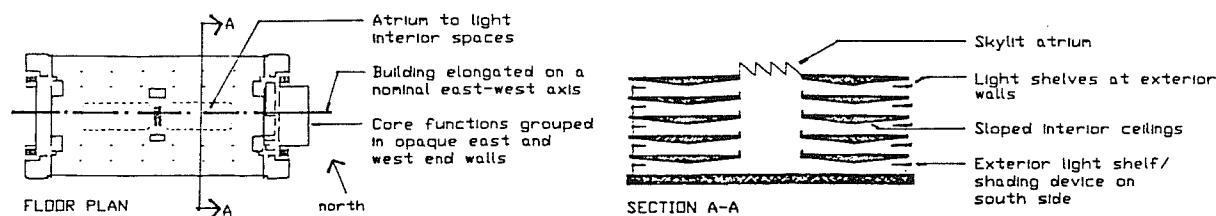


Figure 1. Diagram of building showing daylighting features.

glazed and have an exaggerated floor-to-ceiling height of 15 ft. The building also incorporates ceilings that slope from 15 ft at the atrium and exterior walls to 9 ft at the central corridor. This slope is designed to intercept and reflect illuminance from large light shelves located along both north and south exterior walls. These horizontal interior light shelves are about 7 ft 6 in above the floor and extend inward 12 ft 2 in from the exterior glazing. As indicated in Figure 2, the light shelves create a division between vision glazing below and clear glazing to admit daylight above the light shelf surface. To reduce glare and winter heat gain, the vision glazing has relatively low transmittance. The south side of the building has an exterior light shelf extending 4 ft out from the exterior wall providing additional light collecting area and shading the vision glass below. The central atrium brings additional light to the interior of the building. The entire roof area of the atrium is glazed in a four-bay saw-tooth configuration featuring high-transmittance translucent glazing in the sloped planes.

A target ambient illumination level of 350 lux was established for circulation and casual tasks. This illumination is provided by daylight whenever possible and supplemented by indirect fluorescent ceiling fixtures when necessary. The fluorescent fixtures automatically respond to available daylight with a continuously dimming photosensor-controlled system. This system is capable of dimming the fluorescent lights to 24% of full power (representing 20% of full light output) in response to available daylight. Additionally, a separate computer-based control system turns the lights off during scheduled periods of low occupancy. The LBL investigation examined both the ability of the daylighting architectural features

to provide the targeted illuminance levels and the response of the automatic dimming system to the daylight provided. Separate papers have reported the performance of the electric light dimming system and its related energy savings. [1,2] This paper discusses the performance of the architectural daylighting features with an emphasis on the relative effectiveness of the light shelf system for north and south orientations. This is of particular interest because most studies of light shelf performance [3,4,5] have provided mixed conclusions regarding their effectiveness. This building utilizes light shelves on a scale much larger than previously attempted.

2. NORTH AND SOUTH BUILDING SECTIONS

The design of any daylighting scheme is complicated by the fact that the four cardinal orientations have very different solar performance characteristics, and this variation must be accommodated within an integrated architectural response. In the building studied, the design solution limited major glazing to only two facades, the north and the south, reducing the complexity of this challenge. The resulting design uses a single strong architectural vocabulary of linear horizontal light shelves running the full 400-ft length of the building on both the north and south sides. The design thus represents a flexible solution with a geometry capable (with minor modifications) of accepting both the beam-dominated daylighting of the southern exposure and the diffuse-sky conditions of the north. An interesting aspect of this study was to evaluate the dramatically different light qualities this scheme produces for the two orientations.

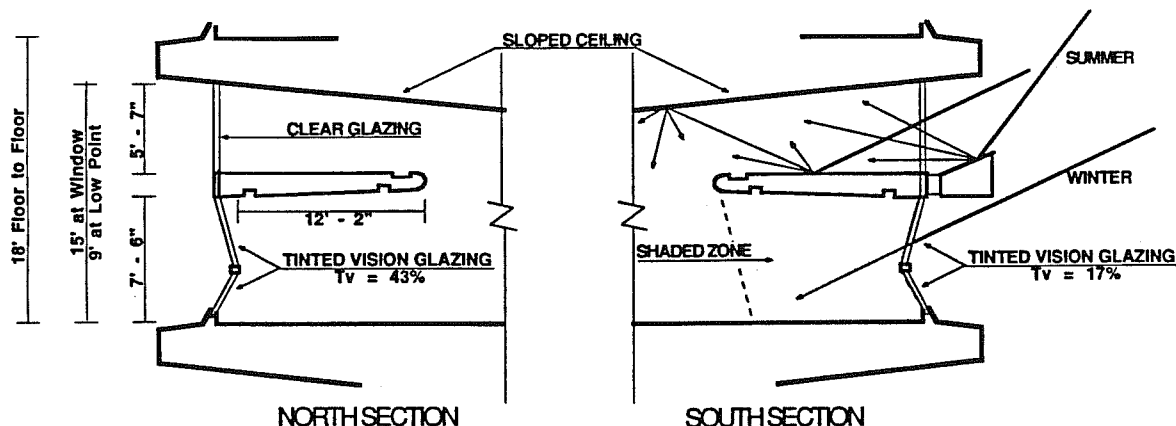


Figure 2. Schematic section through south-side and north-side light shelves.

Schematic sections of the north and south exterior walls are provided in Figure 2. (In this paper, we shall refer to the 45-ft section of the building from the exterior wall to the center-line corridor as the "exterior zone" and the 45-ft section from the atrium edge to the center-line corridor as the "atrium zone".) The south side design is strongly influenced by beam sunlight. Its additional exterior light shelf serves three functions in controlling this intense direct light: its upper white angled surface reflects high summer beam sunlight far into the building's interior; it screens direct view of the sky vault to reduce glare; and it shades the view glazing from sun during the summer. In fact, its geometry is such that the view glazing is fully shaded from direct-beam sunlight in the summer, causing the adjacent area to be darker in the summer than in other seasons. To reduce glare and winter heat gain, the vision glazing below the south light shelf has a relatively low transmittance of only 17%.

Since the building faces about 25 degrees west of true south, the north exterior zone receives a sharp burst of early-morning direct-beam sunlight. The rest of the day, however, it gets only diffuse northern light, giving it an entirely different daylighting character. The north sky provides softer light into this zone, which has higher-transmittance view glazing (43%) and no exterior reflector. The absence of the exterior reflector shading the view glazing in summer months causes this region to be brightest during the summer season.

Both the north and south sections are open to the atrium from about 2.5 ft above the floor to the full 15-ft ceiling height. The office areas adjacent to this open span gain their primary natural light from the atrium's glazing high above. This provides natural lighting with a strong downward component. Although the original design proposal called for smaller light shelves lining these atrium openings to redirect the light deeper into the interior, these were eliminated due to budget constraints.

3. QUALITATIVE IMPRESSIONS

Our measurement program was begun with a series of preliminary site visits. A visual inspection of the building, supplemented with snapshot measurements using hand-held instruments, provided early insight into the differing characters of these north and south sections. Although the dimly lit entry lobby on the south side was not well developed in the daylighting scheme, one moves quickly past this to the central atrium, which presents a pleasant brightness and serves as a focal point of the building. From escalators rising through the atrium's center there are views in each direction of the surrounding office spaces. The atrium provides a definite dramatic flair to the space and offers welcome relief to an open-office plan of this size. At the same time, due to its extensive glazing the atrium always seems more the location of light than a source of light. Though the offices surrounding the atrium are adequately lit, they seem dim in comparison to the brightness of this center space. Light from the overhead atrium glazing ranges from a strongly diffuse character on the south side of the atrium to slightly directional light on the north side. On both the south and north sides of the atrium illuminance levels drop off rapidly as one moves away from the atrium edge.

Overall, the south-side exterior zone appears quite bright and has a dynamic light quality through the year (an impression confirmed by spot illumination readings exceeding 1500 lux 20 feet from the exterior wall). However, this bright appearance doesn't apply to the area directly under the light shelf and adjacent to the view glazing. This area seems relatively dim, and its low-transmittance view glazing appears dark when compared to the clear glazing above the light shelf. To compound this problem, interior horizontal venetian blinds have been retrofitted to the south-side exterior view glazing. Although they are usually retracted, the blinds are dark in color and their presence at the window head further reduces the transmission of light. In contrast with the view windows, the clear glazing above the light shelf is occasionally a source of glare.

The north-side exterior zone, on the other hand, appears to have a more even distribution of light. This side seems dimmer than the south, and it has neither the extreme high nor low illuminance levels apparent in the south side. Glare is not a problem on the north exterior zone, but can be problematic at the atrium edge. Overall, the north has a less dramatic lighting quality that shows little variation with changes in season or weather conditions.

In their differing characters, the building's two exterior zones are not unlike the tortoise and the hare. The south side is exposed to a more volatile environment with rapid changes in beam radiation. It consequently exhibits periodic excesses in quantity and variability of natural light. The northern side has a much calmer character related to the consistent diffuse light from exterior skies that varies slowly and over a smaller range.

4. QUANTITATIVE EVALUATION

The measurement of an existing, occupied building poses some interesting technical challenges. Instrumentation must be installed with minimal disturbance to the building occupants and with an orderly routing of sensor wiring. Our data-acquisition strategy was based on the deployment of four battery-powered dataloggers to collect readings at 28 sensor locations. Measurement locations were changed at three-week intervals. The use of four Campbell Scientific Model CR-21 dataloggers allowed relatively short analog sensor wiring runs and flexibility in sensor placement. Data were stored on digital cassettes and downloaded in the field to a portable microcomputer for off-site evaluation. Characterization of interior lighting patterns was based on LiCor 210S photometric sensors. Illuminance profiles across both the north and south building sections were obtained from a series of ambient illuminance measurements taken in a horizontal plane at partition height, 5 ft 8 in above the floor. Additional photometric sensors were located in the volume above the interior light shelves. Lighting power demand for individual lighting circuits was monitored by Ohio Semitronic PCS-59C watt transducers in the local electrical closet. A third set of sensors measured representative air and surface temperatures at selected locations.

Data were collected from February 1985 until January 1986. Preliminary site visits with hand-held instrumentation established the third floor as a representative floor. Data were recorded for

three-week periods across a horizontal section of the south side of the third floor, then across a similar profile of the north side and finally in a vertical section across all floors along the atrium edge. Data sets were obtained during the summer, equinox and winter. All of the data presented in this paper represent summer conditions and thus should not be extrapolated beyond that season. This paper describes the net performance of the daylighting design which is based on a complex interaction of the optical properties and geometries of the individual daylighting components (light shelves, atrium, sloped ceilings, etc.). Lab measurements, using a scale model of the light shelf in a large integrating sphere, is now in progress to disaggregate the relative importance of each parameter. The results of this work will be reported at a later date.

5. COMPARISON OF NORTH-SIDE AND SOUTH-SIDE DATA

To establish the performance of the daylighting system independent of the electric light dimming system, we have analyzed illuminance data from a series of unoccupied summer days in which there is no electric lighting component. (The absence of electric lighting during these days was confirmed by examining concurrent lighting power consumption data.) These monitored performance data substantiate many of the qualitative observations.

Typical data for interior illuminance under summer clear-sky conditions are shown in Figure 3. The

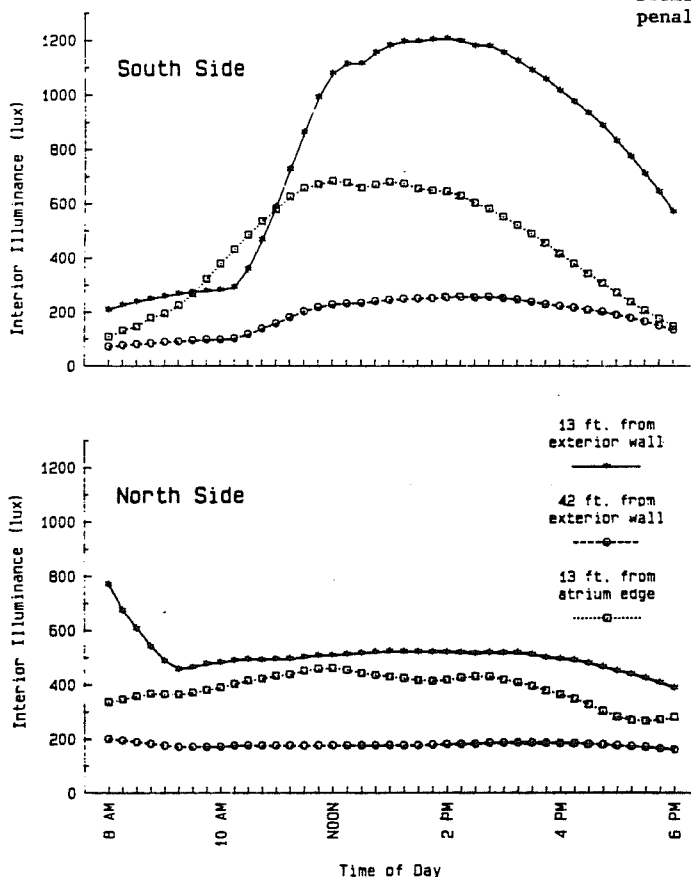


Figure 3. Interior illuminance on a horizontal plane 5'8" above the floor. Data represent the daylight component on a typical, clear summer day.

south side of the structure, strongly influenced by beam sunlight, exhibits substantial variation in illuminance throughout the day. Interior illuminance is low during the morning hours but rises quickly as direct sunlight strikes the exterior light shelf. Peak illuminance readings 13 ft from the exterior wall exceed 1200 lux, almost four times the target of 350 lux. Summer represents the darkest season for this area and winter levels can reach well above 2500 lux. Illuminance levels 42 ft from the exterior wall peak at approximately 250 lux. Though this does not provide 100% of the ambient illuminance, it does reduce the electric lighting load significantly.

As anticipated, the north side of the building has a substantially different daylighting character. Interior illuminance for this diffuse-light-driven scheme does not reach the high levels of the south side, though there is a peak at 800 lux (due to the early morning burst of beam sunlight from its slightly north-east orientation). Except for this anomaly, the north-side illuminance curves are relatively level. All monitored positions show fairly constant levels of illuminance throughout the day. Again the center aisle position is below the 350-lux target but on the average provides the same level of illumination as that found on the south side. The sensors 13 ft from the atrium and 13 ft from the exterior wall show illuminance levels somewhat above the 350-lux target. By comparison, the generally higher illuminance levels of the south side indicate an overperforming daylighting system with potential energy penalties from excess HVAC cooling loads.

Figure 4 shows sectional illumination profiles across the north- and south-side sections on a clear sunny summer day. The sharp illumination gradients at the atrium edges are evident. Confirming the qualitative observations, this graph also clearly shows the drop in illuminance under the south-side light shelf, an area that never exceeds the 350-lux target illumination level.

6. ELECTRIC LIGHT DIMMING POTENTIAL

Data from these unoccupied summer days was used to evaluate the electric light dimming potential inherent in the building's available daylight. Illuminance readings for 24 locations across the north-south building section were collected at 15-minute intervals for normally occupied hours (8 A.M.-6 P.M.) and sorted into bins with 70-lux increments. The general patterns of this illuminance data are summarized in Figure 5. The number of occurrences in each bin was multiplied by the lighting power percentage required to raise that bin to the 350-lux target illumination level. Finally a summation of electric energy required by each monitored location was weighted by the cross-sectional area represented by that location. The results portray the supplemental electric power theoretically required to meet target illuminance levels of 350 lux. From these figures the electric light dimming potential can be determined.

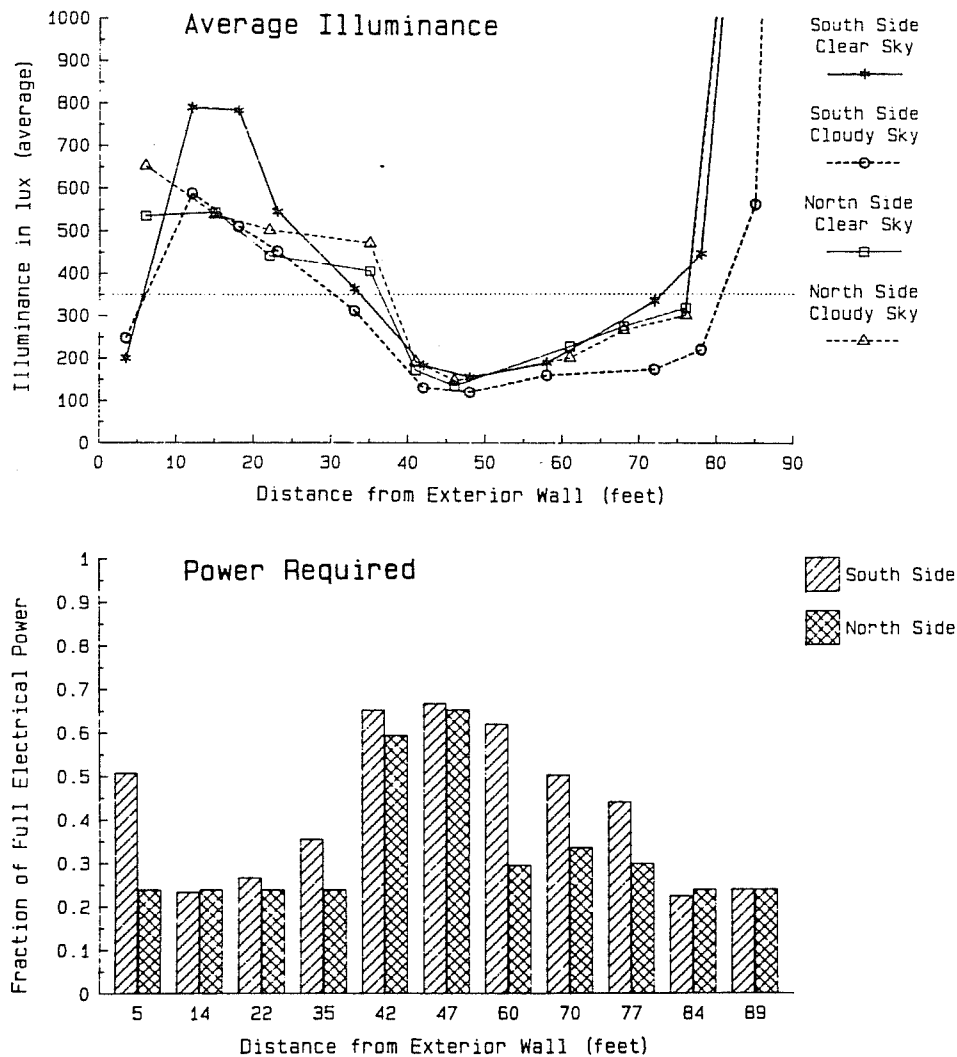


Figure 4. Average interior illuminance and lighting power theoretically required for typical summer conditions. The illuminance data represent daytime averages (8AM - 6PM) for the daylight component only. Power required to achieve the 350-lux target illuminance is based on calculations for the same period.

The binned illuminance data for the south-side exterior and atrium zones show some interesting trends. As might be expected, the south exterior zone with its relatively high light levels demonstrates considerable potential for dimming. The calculations indicate that for occupied hours during this summer period, the zone only requires 39% of the lighting potentially available from the indirect ambient lighting system. The area directly beneath the light shelf is responsible for about a quarter of the electric lighting requirement, as is the zone nearest the central corridor. One would intuitively expect the central corridor area (45 ft from the exterior wall) to require supplemental lighting; but ironically, the area below the light shelf, the zone with greatest access to daylight, requires continuous supplemental light.

The south-side atrium zone, receiving only diffuse daylight from the atrium, requires higher levels of supplemental electric light, 50% of full lighting power. When combined with the south exterior zone performance, this reflects an average elec-

trical power requirement of 44% for the south side.

A similar analysis of the north side's dimming potential provides results that are counter-intuitive at first inspection. The north side of the building, without the strong beam illumination component of the south side, requires less supplemental electrical lighting. Although the north side lacks the high daylight levels found on the south side, it consistently has enough daylight to meet the 350-lux target level. Consequently the "darker" north side exhibits a higher potential for electric light dimming than the "brighter" south side. Our calculations indicate that the north exterior zone requires only 26% of the possible electric ambient lighting as a supplement to daylight. The north atrium zone also compares favorably with the south side in requiring only 35% of potential electric lighting. Only the center corridor area of the north side requires substantial electrical lighting. The north exterior and atrium zones combined require an average of 31% of full electrical power.

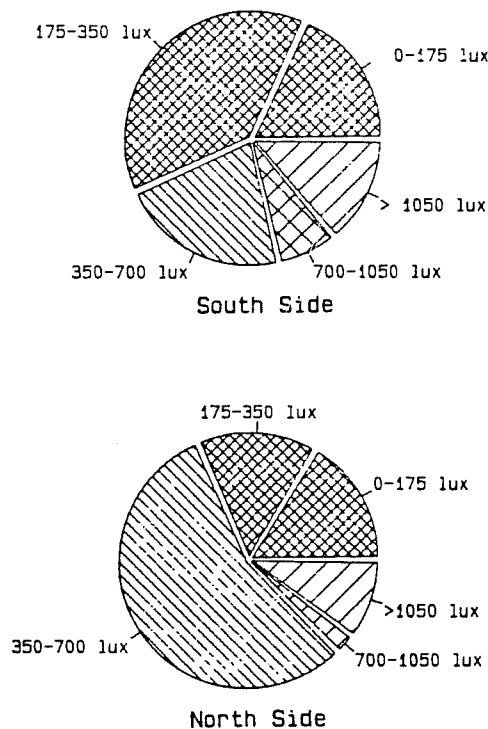


Figure 5. Distribution of interior illuminance levels over a typical unoccupied summer day.

The distribution of required electrical lighting power (as a fraction of full power) across both the north- and south-side building sections is summarized graphically in Figure 4. (Note that because of the electrical operating characteristics of the dimming system the ambient electric lights cannot be dimmed to below 24% of full power.) These calculations provide an impressive index of the electrical light savings that are made possible by the interior illumination delivered by the architectural features of the building. Based on our summer-period data, the average energy consumption figure for north-side and south-side zones combined is 37% of full power, reflecting 62% dimming of the electrical ambient illumination system.

7. CONCLUSIONS

This study has shown that the architectural daylighting features are performing well in providing for the ambient lighting needs of this building and can potentially produce significant reductions in electrical energy consumption. Based on the summer-period data reported here, potential energy reductions down to 37% of full power can be expected for the ambient lighting system. The actual measured savings are less than this. [1] However, relatively simple changes in the placement of the sensors for the electric light dimming system should improve the measured performance.

Although the north side doesn't have the dynamic lighting qualities of the south side, overall it out-performs the south in achieving the 350-lux target illumination level. The electric light

dimming potential of the north side is only 31% of full power, compared to 44% for the south.

The more intense lighting levels of the south side do not provide additional benefit in the form of electric light dimming because they exceed the target level for ambient illuminance. There are perhaps savings from these high light levels in the displacement of task lighting in the south exterior zone, but once the 350-lux target level has been achieved, surplus light becomes more of a liability because of increased solar heat gain.

The combination of very-low-transmittance glazing (17%) and shading by the exterior light shelf makes the south exterior zone under the light shelf one of the dimmest areas in the building. Though it potentially has abundant access to daylight, it requires continuous supplemental light in the summer months.

The central atrium gives a dramatic flair to the space and offers a pleasant visual focus to this large-scale, open-plan office structure. At the same time the strong downward component of its daylight is less effective at providing light deep into adjacent interior spaces. The atrium edge is the location of a sharp gradient in natural light levels.

In this study, we focused on the quantitative aspects of daylighting analysis. The building's occupants are generally pleased with the overall lighting quality, but extensive post-occupancy surveys have not yet been performed.

The monitoring of daylighted buildings to evaluate the performance of their daylighting schemes provides significant insights into the complex interactions of the daylighting components and the dynamic nature of natural light. The information gained is sometimes counterintuitive and is an invaluable addition to our knowledge of the effective use of daylight in buildings.

8. ACKNOWLEDGMENTS

This study was supported by the Energy Services Department of the Pacific Gas and Electric Company and by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U. S. Department of Energy under contract No. DE-AC03-76SF00098. Valuable assistance was provided by the building owner and architect.

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